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Radioactive convergence of nuclear leakage in Fukushima: Economic impact analysis of triple tragic events

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ABSTRACT

The novelty of this study is to investigate if there is radioactive convergence around Fukushima city of Japan as a result of earthquake and tsunami in March 2011. The research also aims to investigate whether the other nearby cities located around Fukushima city shared any common convergence experience following the first two weeks of the March 2011 explosion, which all might be affected by this tragic chain of events. Two kinds of convergence have been examined: beta and sigma. For the entire period of 15–27 March 2011, only sigma convergence has been observed. The research findings did not confirm any beta convergence for the entire period. However, for the sub-periods (first week, first half and second half of the second week), more significant results have been found both for beta and sigma convergences of radioactive contamination. The data used in this study covers the period of 15–27 March 2011 on hourly bases in order to analyze the catching-up process between six cities surrounding Fukushima which are affected from the catastrophe.

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1. Introduction

There has been a vast amount of research on the convergence theorem, in particular, income convergence. Some of the most related convergence studies will be reviewed in Section 3; and in this study, radioactive convergences will be estimated which occurred as a result of Fukushima Daiichi's nuclear power plant explosion. Uncontrolled leakage of radioactive materials beyond the vicinity of the plant and the continuous leakage has threatened human life within 60 km radius of Fukushima which was verified by the Green Peace measurements. Methodologically, most studies about convergence of incomes and growth have been undertaken in the literature by using time series econometrics and therefore the same empirical methodology will be applied over here. Some of the studies have been carried out on regional convergence by using cross-sectional or regional panel techniques, especially for the Caribbean, Latin American and Asian economies [1–3]. It is also possible to conduct such a similar convergence study on a specific country case or on a region which, for example, has already been implemented by Michelis et al. [4] for Greece.

The methodology in this study rely on panel data econometric procedures including panel unit root tests and panel regression models to estimate absolute beta (β) and sigma (σ) convergences [5]. The

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speed of convergence in time is based on the catching-up process of nuclear radioactive contamination among the regions of Fukushima Prefecture. The empirical methodology for estimating β and σ convergences is explained in details in Section 4 of the present study. Many convergence studies concentrate on the growth of income either regionally or among the nations; however, this methodology has been amended and implemented over here to identify empirically the growth of radioactive contamination and changes in development levels in different cities of Fukushima based on Green Peace statistical data. Protecting human life becomes the most crucial concern for scientists in making an immediate decisions about evacuation. Life danger might differ among regions as a result of the proximity of danger zone, and the speed of nuclear contamination spreading over the region due to the failure of cooling off nuclear systems at the Fukushima Daiichi Plant.

This study is organized in six sections. After introduction, Section 2 summarizes the economic impact of the March 11, 2011, events in Japan. Section 3 briefly reviews the convergence debate in related literature. Section 4 explains the empirical methodology of convergence with special attention to beta (unconditional) convergence and sigma (conditional) convergence of nuclear leakages that might have an impact on Iwaki, Soma, Lidate, Tamakawa, East Tamura and West Tamura, which all are located around Fukushima City within 60 km radius. Section 5 includes data sources and highlights the main findings. Finally, Section 6 highlights principal conclusions and follows policy implications.

2. The economic impacts of 11 March triple disaster in Japan

One of the ultimate goal of this study is to find out whether the surrounding cities of Fukushima have been involved with radioactive contamination from the incident of nuclear meltdown.

As emphasized by Matanle [6], a magnitude 9.0 reverse fault megathrust earthquake occurred 100 km east of the Miyagi Prefecture in Japan (March 11, 2011) and a huge tsunami with a provisional maximum recorded height of 17 m which swept over the low-lying coastal areas of the north-eastern seaboard of Honshu, flooding more than 507 km^2 of land and leaving 26.7 million ton of debris in its wake. Uncontrolled leak of radioactive materials beyond the vicinity of the Fukushima's nuclear plant as a result of meltdown of some of the reactors (1–3) urged a 3 km of immediate evacuation zone, which was widened to a 10 km and then a 20 km radius, while residents 20–30 km from the plant were urged to remain indoors. The government declared the 20 km zone a no-go area and danger zone has been expanded up to 60 km radius due to high radiation levels being detected [7,8]. The decision of government on evacuation has initiated us to investigate the speed of radioactive contamination (growth of radioactive contamination) at several periods and the impact of radioactive convergences on 60 km radius of Fukushima city.

Besides loss of human life, natural disaster and nuclear meltdown caused huge economic losses on properties, tourism, farms, fishing, livestock and all other manufacturing activities. The economists are therefore interested in planning the post-disaster reconstruction and food security for Japan.

Swift [9] has emphasized that Japanese manufacturers in the automotive, consumer electronics, steel and paper sectors have taken the factories offline, and several major refineries were shut down immediately after the disasters. According to Swift [9], Japan's consumer spending and business investment will be dampened in the short-term, and growth and economic activity is expected to pull down. This situation will inevitably affect the imports of other nations from Japan, especially for products primarily sourced in Japan, such as light vehicles, automotive parts, and electronics. The shortages of imported parts for vehicle manufacturing will surely affect many countries' assembly plants.

Guo et al. [10] have assessed building damage by overlaying seismic intensity and building distributions. In addition to that, they have assessed the extent of building and farm damage caused by tsunami through the establishment of the tsunami impact assessment model that is based on terrain and distance from the coastline, surface roughness and other factors. The model is formulated as follows:

$$F = f(H + kD) \tag{1}$$

where H is the altitude difference between the evaluation point and sea level. The research is based on Global Digital Elevation Model (GDEM) data, which were provided by the Japanese Economy and Industry (METI) and NASA. Parameter D in the above formula represents the distance from the coastline and k represents the attenuation coefficient, which can be determined as the value of the reduced wave height when the tsunami advanced 1 m over the ground. Parameter k is affected by surface roughness characteristics of tsunami itself and other factors. The value of $(H+kD)$ represents an evaluation that is based on the comprehensive consideration of terrain features and the distance from the coastline. The function f, through a certain transformation, can quantify the degree of impact by the tsunami. A segmentation approach has been used in that study by which the most heavily damaged areas were partitioned into areas of highly serious impact, serious impact, general impact, and no effect. According to the findings of Guo et al. [10], about 76 percent of buildings in Miyagi Prefecture were affected by seismic intensity 6 and above, with 24 percent of the buildings and 12 percent of the farms destroyed by the tsunami. On the other hand in Fuhushima, about 53 percent of buildings were affected by seismic intensity 6 and above, with 15.2 percent of the buildings and 7.6 percent of the farms destroyed by the tsunami. House collapses, wall cracks, grave stones and stone lanterns collapse, chimneys damage, landslides, ground cracking, and faulting were observed after the assessment.

Butler et al. [11] emphasized that the nuclear reactors at the Fukushima site were all safely shut down, but subsequent power outages caused by the tsunami resulted in a failure of the cooling systems, eventually leading to a release of radioactive material across four units. As TEPCO [12] highlighted, radioactive leakage continues, and on 17 April, Tokyo Electric Power Company (TEPCO), owners of the plant, estimated that it will take 9 months to bring the plant under control. Butler et al. [11] stressed that while the full extent of radiation leakage is yet to be determined, lethal levels of radiation had been detected at the site, raising concerns about the scale of the impacts, particularly for workers. Emmott [13] also underlined that the scale of the disaster in Japan's tragic event will be unknowable until the nuclear dangers have either transpired or been brought definitely under control. NHK [14] and Nikkei.com [15] mentioned that engineers from Toshiba and Hitachi, two of the three companies that built the reactors and turbines at Fukushima Daiichi (the other being General Electric), estimate that it will take between 10 and 30 years to complete decommissioning Fujushima Daiichi. Tamaki and Toyoda [16] pointed out that complete decommissioning will likely cost in excess of 12 billion US dollars.

Total costs will certainly fall on the state of Japan since nuclear power plants are not insured commercially. Japan's gross public debt has exceeded 200 percent of GDP [17]. Japanese government should borrow more money at this time of national crisis for regional reconstruction and revitalization. Shrinking economy of Japan will increase the economic debt burden, for which a special reconstruction tax will probably be levied and Japanese people

will be entirely prepared to make sacrifices from their personal spendings and income in order to share the national burden.

Matanle [6] also brings into attention that the Japanese government has established an office for managing the economic impacts of the nuclear crisis, which will work with TEPCO to compensate those who were affected from the nuclear contamination. TEPCO has offered 1 million Japanese Yen as a preliminary payment to each household directly affected [18] and outlined a plan for those who have suffered losses due to negative rumors, such as tourism businesses, farmers and fishermen in Fukushima Prefecture and some other areas [19].

According to Butler et al. [11] the expenditure for compensation alone is estimated to be 124 billion US dollars, the costs of which will be covered in the first instance by special government-issued bonds that the private owners of the Fukushima power station (TEPCO) will be expected to repay over and yet an unspecified number of years. Well known automobile companies, such as Honda and Toyota reported 50 percent decline in their 2011 production [20], domestic and foreign tourist dropped by 50–60 percent following the disaster, and farming and fishing communities have suffered income losses due to radiation and loss of public trust in food safety. Livestock within the evacuation zone has also been abandoned and all animals that remain alive have lost their economic value [21].

The Economist [22] analyzed that the early estimates put the recovery cost at 200 billion US dollars, but will rise, as the nuclear cleanup and decommissioning were not included in these calculations. Power shortages will also slowly recover. Dickie [23] also considered that the economic cost will be in the range of 3–5 percent of GDP, as against 86 and 29 percent for previous watershed events such as the Second World war and Great Kanto Earthquake respectively.

Horwich [24] accentuated that one of the most expensive reconstruction operation in the world history was the 1995 Great Hanshin earthquake, costing approximately 64 billion US dollars in terms of capital stock and the regional economy had almost completely recovered within 15 months of that disaster.

Matanle [6] stressed that the Japanese are a resourceful and knowledgeable people and possess deep wells of self-discipline and determination, and these attributes will stand them in good stead. Considering the shrinkage of working age and children's population, high rate of migration from rural to urban cities, the opportunity of rapid expansion in affected areas will be more difficult. Based on these facts, Matanle [6] raised some difficult questions about the structure of governance and policy making in Japan, the direction of Japan's post-war development, and the degree to which reconstruction plans are affordable and realistic.

As highlighted before, the devastating nuclear danger is not precisely known yet; this research aimed to contribute to the literature, how to measure the growth and speed of radioactive contamination level through beta and sigma convergences approach. It is therefore aiming to fulfill the gap in this field of research as a unique and timely study.

3. The review of convergence debate

The subject of convergence is vast [25] as it occupies a central place in theories of growth and inter-regional trade. Given perfect competition and factor mobility, the theorem, derived from diminishing returns to scale, reaches the policy-rich conclusion that real income per capita between a rich and poor region converges, relative to a steady state growth [26] pattern. In other words, in the long-run, incomes equalize as diminishing returns per unit of output fall in the higher income region while the lower income region enjoys higher returns for the same level of savings and investment. Therefore, the poorer region can "catch up" to the richer one, achieving absolute convergence. How rapidly this equalization can be realized depends on the rate of convergence, for example, capital deepening due to free capital mobility and cost-free exit.

In the literature, two measures of convergence are recognized. One is the absolute (unconditional) beta (β) convergence, and the second is the sigma (σ) or conditional convergence [25]. It is linked with the notion of dispersion of incomes between regions at a point in time, and how fast the dispersion, measured by standard deviation, is reduced. There is also conditional, or club convergence, which refers to a set of regions converging not to a single equilibrium level of (common) income, but rather to different equilibria conditioned by case-specific technological or policy environments [25].

In beta convergence analysis, the growth is assumed to be realized without any condition with respect to Solow's [26] steady state theorem. Based on the same approach, this study will concentrate on the implementation of beta convergence of radiation level growing unconditionally within the regions of Fukushima, regardless the distance and technological capabilities of cities located within 60 km radius. The sigma convergence makes the growth process conditional on technological capabilities with respect to productivity growth. Solow's optimistic approach is based on the countries income level and emphasize that the farther a country's GDP is from its steady state, the faster it will grow in subsequent years. The predictions are known as the convergence hypothesis. As mentioned above, the convergence hypothesis would predict that countries with low initial per capita GDP will grow faster than those that started up richer, which are presumably closer to their steady state. The methodology of convergence hypothesis is generally applied to measure the speed of convergence in time. Since time of convergence is the initial aim to be measured, differing from the income convergence, this study focuses on the implementation of the σ convergence hypothesis on measuring the speed of radioactive contamination convergences among the cities of Fukushima Prefecture during the time of crisis of March 2011. The data used in this study is collected from the sources of Green Peace Organization [27] and covers the period of 15–27 March 2011 on hourly basis. Total 314 observations regarding the measurement of radioactive contamination have been used to analyze the catching-up process among the mostly affected cities around the nuclear region.

The recent debate on growth and convergence has also resulted in extensive empirical studies and applications. Barro and Sala-i-Martin [28,29], Atkins and Boyd [1], Dobson and Ramlogan [2], Zhao [30], Rapacki and Prochniak [5], Yorucu and Mehmet [31] and Yorucu [32] have implemented beta and sigma convergences in their studies selectively to a group of countries or regions.

4. Theory and empirical methodology of convergence

This study focuses on evaluating empirically the regional radioactive convergences among the cities, which are located in the region of Fukushima Prefecture, namely Iwaki, Soma, Lidate, Tamakawa, East Tamura and West Tamura. Panel unit root and panel regression tests have been carried out throughout this study. This study focuses on two concepts of convergence: absolute (unconditional) beta (β) convergence and sigma (σ) convergence. The data used in this study covers the period of 15–27 March 2011 on hourly basis in order to analyze the catching-up process of nuclear radioactive contamination among those cities.

Rapacki and Prochniak [5] stated that beta (β) convergence occurs when less developed economies with lower per capita income tend to grow faster than more developed ones with higher

per capita income. Over here, the assumption has been amended in a way that nearest cities located around Fukushima (with 20 km distance) with higher level of nuclear radioactivity is catching up quicker to the farthest cities (with 60 km distance) with lower level of contamination. Empirically, beta (β) convergence can be estimated with the following regression equation as stated below:

$$\frac{1}{T}(\ln \gamma(T) - \ln \gamma(0)) = \alpha_0 + \alpha_1 \ln \gamma(0), \tag{2}$$

$\ln \gamma(T)$ is the nuclear radioactive contamination level in the end of the relevant period and $\ln \gamma(0)$ is the nuclear radioactive contamination level in the initial period. The $T+1$ is the number of periods (hours or time trend), which for this study represents the period of 15–27 March totaling 314 h (T_1–T_{314}). When the estimated coefficient of α_1 is negative, then beta (β) convergence can be realized. Once the beta (β) convergence occurs, then the beta (β) coefficient can be calculated with a formula given below. This formula which is derived from the Solow model [26,33] conveys information on the speed of convergence.

$$\beta = -\frac{1}{T}\ln(1+\alpha_1 T). \tag{3}$$

The calculated β coefficient over here indicates the percentage of the distance towards the constant rate of nuclear radioactive growth (steady state growth) a city is covering during one period. Keeping in mind that β coefficient here indicates us what percentage of the distance towards the constant rate of nuclear contamination a city is covering during one period. It is our interest to investigate here whether any cities exhibit a decelerating growth rate of contamination as measured by the σ convergence approach. For this study, in the process of absolute convergence, it is assumed that all surrounding cities of Fukushima in question tend to reach the same level of nuclear radioactive contamination rate (constant growth of nuclear radioactive contamination level as alike the principle of steady state growth). It is assumed that all cities narrow their distance towards the constant rate of contamination level in the same percentage term, reaching the same level of contamination at the same moment and the distant cities of Fukushima region covers a longer distance than the nearby ones. The nuclear radioactive contamination between the cities must show up the catching up trend. It is very important to highlight that the β coefficient does not measure the actual pace of nuclear radioactive contamination equalization; rather, it shows the speed of radioactive convergence towards the hypothetical constant growth rate.

Sigma convergence occurs when α_1 is negative. In order to test the occurrence of σ convergence, the following regression equation can be estimated:

$$sd(\ln \gamma(t)) = \alpha_0 + \alpha_1 t, \tag{4}$$

where $sd(\ln \gamma(t))$ is the standard deviation of the log of nuclear radioactive contamination rate between cities per hour of t and t is the time (t=1, 2,…, 314).

The radioactive contamination differentiation can be measured by the standard deviation of nuclear radioactive contamination levels between cities. As also specified by Rapacki and Prochniak [5] estimating the trend line is not always the best way to test the sigma convergence for two reasons. The first reason is that the contamination level differences can change non-linearly and second reason is that, this method does not necessarily enable the researchers and the practitioners to detect the exact tendencies of contamination differentiation in individual hour. Taking these constraints into consideration, it is suggested that for the verification of sigma convergence, the hypothesis may be best accomplished through reading out the directions of change of radioactive contamination standard deviation from an appropriate chart or figure. Keeping this in mind, with a view to ensure the transparency of this article, the format of this study is divided in four periods: the entire period of 15–27 March 2011 (314 observations) and the periods of 15–21 March (first week of the nuclear meltdown with 160 observations for each series), 22–24 March (first half of the second week with 75 observations) and 25–27 March (second half of the second week with 73 observations).

The concept of β and σ convergences was also implemented by Atkins and Boyd [1] for the Caribbean nations through applying the Solow–Swan model. It is possible to drive an estimation equation for individual country convergence through constructing the following equation :

$$\Delta y_t = \beta_0 + \beta_1 t + \beta_2 y_{t-1} + \varepsilon_t \tag{5}$$

where y_t is the level of nuclear radioactive contamination, β_0, β_1 and β_2 are the estimated parameters, t is the time trend and ε_t is a random disturbance error term (or called white noise error term). If we want to elaborate β in more detail, β=$(1-\alpha)(n+g+\delta)$ is the speed of convergence, indicating the pace at which the level of nuclear radioactive contamination reaches its constant growth rate. Beta convergence is concerned with the question of whether, when analyzed from a common start date, the distant cities (within 60 km radius) from the region of Fukushima Prefecture can be contaminated at a faster rate than the nearby ones so as to catch up to the contamination rate of Fukushima.

In cross cities estimations, which are implemented in this study for the group of selected cities within 60 km radius of Fukushima, it is usual to assume the same region (geography), if there are differences in wind direction (climatologic changes), technical capabilities or competency in nuclear management and this would imply different n_i and s_i so that β and γ would vary. For the group of selected countries or cities (also called 'club'), these variables are considered constant across countries or cities, so that the new estimation equation becomes

$$\ln \gamma_{it} = (1-\beta)\ln_{it-1} + \beta(\ln \gamma^{*}_{i0} + gt) + \varepsilon_{it} \tag{6}$$

where the error term (ε) reflects the shocks. Therefore the above equation can be reconstructed in a way such as

$$\ln \gamma_{it} = \alpha' + \lambda \ln \gamma_{it-1} + \varepsilon_{it} \tag{7}$$

As pointed out by Atkins and Boyd [1], α' is the weighted sum of the α' and the error becomes a weighted average of different country/city errors, which should not be autocorrelated. It is known in general that beta convergence is concerned with the question of whether, when analyzed from a common start date, poorer countries grow faster than the richer ones, hence generating mean reversion across economies. From this perspective, we have changed our hypothesis over here as the more distant cities of Fukushima has been contaminated in a much faster rate than the nearby ones. This is analyzed by cross-section regressions with the help of the panel study. If $\lambda^T < 1$ then this is the condition of beta (β) convergence.

As stated by Barro and Sala-i-Martin [29] and Quah [34] beta convergence (unconditional) is necessary but not a sufficient condition for sigma (σ) convergence. Sigma convergence additionally depends on whether countries are in fact converging to the same steady states, and also on the strength of the convergence forces relative to the strength and persistence of shocks. Sigma convergence requires that the cross country variance of output decreases over time. Dobson and Ramlogan [2] pointed out that it is common in convergence studies to measure the cross-sectional dispersion of per capita income over time, which is called sigma convergence. This methodology can be implemented on cross-sectional dispersion of radioactive contamination over time among cities as it has been implemented throughout this study.

According to the study of Atkins and Boyd [1], sigma convergence requires that the cross country variance of output decreases over time. Atkin and Boyd's model has been amended over here

and instead of GDP per capita, the level of radioactive contamination has been selected to be analyzed throughout this study. Therefore, a reconstructed model with a replaced radioactive convergence variable has been modeled as follows:

$$Y_{iT} = A + BY_{i0} + \varepsilon_{it} \quad (8)$$

Y_{i0} is the natural logarithm of radioacative contamination for the initial year for city i and Y_{iT} is the natural logarithm of radioactive contamination for the final year for city i. From the equation given below for cross-section estimations, the variance of Y_{iT} can be estimated as follows:

$$E(Y_{iT} - \overline{Y}_T)^2 = B^2 E(Y_{i0} - \overline{Y}_0)^2 + E(\varepsilon_{iT} - \overline{\varepsilon}_T)^2 \quad (9)$$

If we reconstruct the above equation, we can have a new equation which is shown below and it is assumed that the covariance between initial output and random shocks to be zero.

$$\sigma_T^2 = B^2 \sigma_0^2 + \sigma_\varepsilon^2 \quad (10)$$

Dividing the above equation by σ_T^2, the variance can be written as

$$1 = B^2 \frac{\sigma_0^2}{\sigma_T^2} + \frac{\sigma_\varepsilon^2}{\sigma_T^2} \quad (11)$$

The coefficient of determination can then be obtained as

$$R^2 = 1 - \frac{\sigma_\varepsilon^2}{\sigma_T^2} \quad (12)$$

which can be simplified as a new equation such as

$$\frac{\sigma_T^2}{\sigma_0^2} = \frac{B^2}{R^2} \quad (13)$$

Shortly, decreasing variance implies that the cross-section ratio between time T variation and initial variation should be less than unity, i.e. $\sigma_T^2/\sigma_0^2 < 1$, and this condition for sigma convergence may be written as $B^2/R^2 < 1$.

5. Data sources and findings

In this section, hourly time series data over the period of 15–27 March 2011 have been used to test the possibility of β convergence and σ convergence around a common long-run growth path. Statistical data about radioactive contamination are gathered from the source of Green Peace [27] for the group of six cities located 20–60 km radius of Fukushima Prefecture where the nuclear reactors of Daiichi Power Plant have been melted as a result of a magnitude 9.0 reverse fault megathrust earthquake and maximum recorded height of 17 m high tsunami. For estimation purpose, we used radioactive contamination series in MP values (dose rates at monitoring posts depend on the situation of radiation around their installation locations) in natural logarithms. Tables 1–4 show panel unit root test results with intercepts and no trends, and with intercepts and linear trends evolving four periods: the entire period of 15–27 March 2011 (314 observations), the period of 15–21 March (first week of the meltdown with 160 observations), 22–24 March (first half of the second week of meltdown with 75 observations) and 25–27 March (second half of the second week of meltdown with 73 observations).

Tables 5 and 6 demonstrate the results of beta and sigma convergences for all periods respectively.

Fig. 1 illustrates the trend lines of radioactive contamination for Iwaki, Soma, Lidate, Tamakawa, East Tamura and West Tamura,

Table 1
Panel unit root tests for radiation leakage (surrounding cities of Fukushima, entire period: 15–17 March 2011).

Variables	Level		
	LLC	IPS	*M–W*
ln(Radiation)			
τ_T	15.471	−0.822	18.179
τ_μ	4.110	0.115	8.368
1st Difference ln(Radiation)			
τ_T	26.719	−8.118*	97.996*
τ_μ	21.369	−8.884*	119.904*
2nd Difference ln(Radiation)			
τ_T	207.622	−14.165*	207.223*
τ_μ	186.213	−14.626*	234.886*

Note: ln(Radiation) stands for the natural log of radiation leakage. τ_T represents the most general model with a drift and trend; τ_μ is the model with a drift and without trend. Optimum lag lengths are selected based on the Schwartz Criterion. Tests for unit roots have been carried out in E-VIEWS 7.2.

* Rejection of the null hypothesis at the 1 percent level.

Table 2
Panel unit root tests for radiation leakage (surrounding cities of Fukushima, specific period: first week of March 2011).

Variables	Level		
	LLC	IPS	*M–W*
ln(Radiation)			
τ_T	57.505	3.559	3.151
τ_μ	12.606	2.107	7.947
1st Difference ln(Radiation)			
τ_T	96.365	0.182	14.253
τ_μ	77.488	−1.156	19.371***
2nd Difference ln(Radiation)			
τ_T	289.527	−2.436**	27.117**
τ_μ	285.629	−3.650**	38.319**

Note: ln(Radiation) stands for the natural log of radiation leakage. τ_T represents the most general model with a drift and trend; τ_μ is the model with a drift and without trend. Optimum lag lengths are selected based on the Schwartz Criterion. Tests for unit roots have been carried out in E-VIEWS 7.2.

** Rejection of the null hypothesis at the 1 percent level.

Table 3
Panel unit root tests for radiation leakage (surrounding cities of Fukushima, specific period: first three days of the second week of March 2011).

Variables	Level		
	LLC	IPS	*M–W*
ln(Radiation)			
τ_T	13.466	2.672	4.144
τ_μ	9.685	0.209	8.776
1st Difference ln(Radiation)			
τ_T	25.902	0.159	9.780
τ_μ	21.076	−0.766	14.958
2nd Difference ln(Radiation)			
τ_T	173.297	−2.571*	29.499*
τ_μ	145.496	−3.753*	42.339*

Note: ln(Radiation) stands for the natural log of radiation leakage. τ_T represents the most general model with a drift and trend; τ_μ is the model with a drift and without trend. Optimum lag lengths are selected based on the Schwartz Criterion. Tests for unit roots have been carried out in E-VIEWS 7.2.

* Rejection of the null hypothesis at the 1 percent level.

which are all surrounded with Fukushima City within a 60 km radius.

The numbers in the vertical line indicate the level of radioactive contamination and the hours are indicated on the horizontal line for the period of 15–27 March 2011. Each trend line indicates the level of radioactive contamination. Fig. 2 also shows the same trend lines in natural logarithms.

Each trend line has the name of its city. As Quah [34] emphasized, the trend lines of the figures show us how conditional convergence (σ convergence) is expected to occur as time passes. It is therefore expected to have some σ convergence for the period after the explosion of Daiichi Nuclear Power based on the estimated period 15–27 March. It is the researchers' interest to see whether all cities have been contaminated from the spread of radioactive materials and they converge regardless the distance within 20–60 km radius. The data pooled as a panel study of all six cities and panel estimations are carried out for both β and σ convergences separately.

Considering the convergence methodology in the literature, Islam [35] argues that cross-sectional estimation across countries can be problematic because it is likely that not all of the relevant conditioning variables will be included in a cross-sectional regression. If there are any omitted variables this will introduce non-zero covariance between the disturbance term and the β coefficient, rendering the estimate of the convergence parameter biased and inconsistent. Dobson and Ramlogan [2] suggested that this problem does not arise if the data is pooled and analyzed using panel data methods. It can be established whether it is admissible to pool the data or whether the data should be kept separate by

Table 4
Panel unit root tests for radiation leakage (surrounding cities of Fukushima, specific period: last three days of the second week of March 2011).

Variables	Level		
	LLC	IPS	*M–W*
ln(Radiation)			
τ_T	20.574	−1.904**	22.123**
τ_μ	6.463	−3.734*	34.930*
1st Difference ln(Radiation)			
τ_T	19.990	−3.089*	26.172*
τ_μ	15.699	−3.035*	35.550*
2nd Difference ln(Radiation)			
τ_T	116.148	−4.865*	42.348*
τ_μ	83.435	−5.984*	58.065*

Note: ln(Radiation) stands for the natural log of radiation leakage. τ_T represents the most general model with a drift and trend; τ_μ is the model with a drift and without trend. Optimum lag lengths are selected based on the Schwartz Criterion. Tests for unit roots have been carried out in E-VIEWS 7.2.

* Rejection of the null hypothesis at the 1 percent levels.
** Rejection of the null hypothesis at the 5 percent levels.

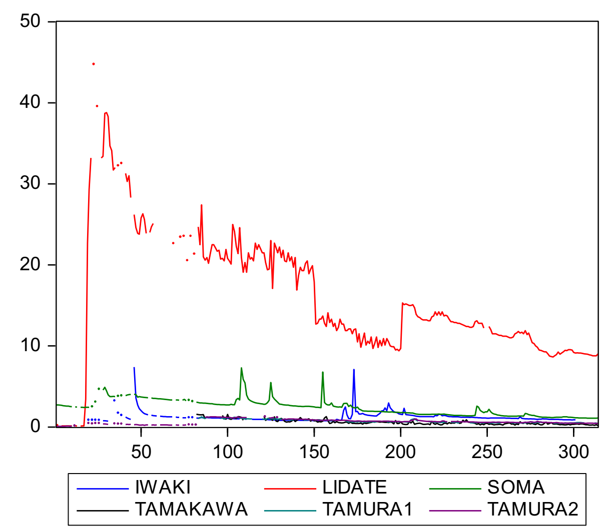

Fig. 1. Radioactive contamination contaminating six cities around Fukushima city (trends in actual form).

Table 5
Regression results for β convergence for all of the cities surrounding Fukushima (white heteroscedasticity corrected).

Period	α_0	α_1	$t(\alpha_0)$	$t(\alpha_1)$	$p(\alpha_0)$	$p(\alpha_1)$	R^2	β-Convergence
15–27 March	0.0034	0.0003	7.330	1.320	0.000	0.000	0.0057	0.00032 No
15–21 March	−0.0080	−0.0080	2.150	−3.780	0.000	0.000	0.730	0.00052 Yes
22–24 March	−0.0006	−0.0011	−3.250	−2.490	0.000	0.000	0.050	0.00115 Yes
25–27 March	0.1691	−0.1886	3.590	−2.380	0.000	0.000	0.039	0.03688 Yes
15–27 March	0.0030	0.0003	1.005	0.152	0.372	0.152	0.005	−0.00032 No
15–21 March	0.0015	−0.008	0.479	−3.292	0.656	0.030	0.730	−0.03166 Yes
22–24 March	−0.0006	−0.001	−0.226	−0.459	0.831	0.670	0.050	0.00114 No
25–27 March	−0.0053	0.0006	−3.323	0.472	0.029	0.661	0.052	−0.00061 Yes

Table 6
Regression results for σ convergence for all of the cities surrounding Fukushima (white heteroscedasticity corrected).

Period	α_0	α_1	$t(\alpha_0)$	$t(\alpha_1)$	$p(\alpha_0)$	$P(\alpha_1)$	R^2	σ-Convergence
15–27 March	0.0081	−0.0015	7.400	−5.910	0.000	0.000	0.201	Yes
15–21 March	1.0721	−0.2090	8.170	−8.430	0.000	0.000	0.334	Yes
22–24 March	0.2771	−0.0642	8.070	−8.430	0.000	0.000	0.408	Yes
25–27 March	0.2515	−0.0487	1.900	−1.600	0.000	0.000	0.084	Yes
15–27 March	1.0809	−0.0032	11.085	−6.351	0.000	0.000	0.026	Yes
15–21 March	1.0721	−0.2094	1.861	−1.416	0.136	0.229	0.334	Yes (nm)
22–24 March	0.2771	−0.0642	1.838	−1.660	0.139	0.172	0.407	Yes (nm)
25–27 March	0.2514	−0.0487	0.803	−0.606	0.466	0.576	0.084	Yes (nm)

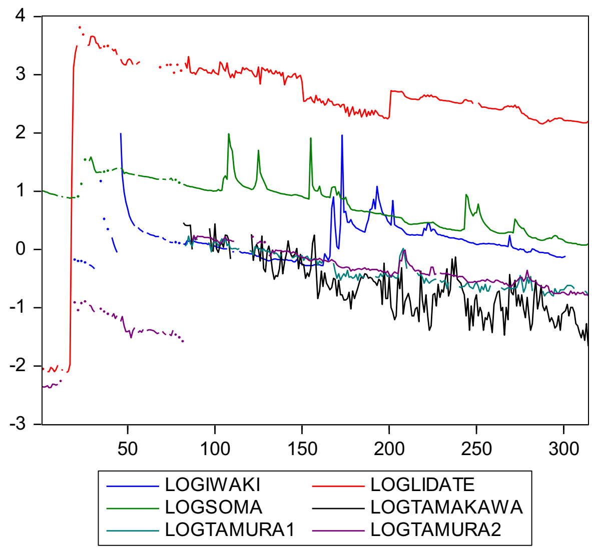

Fig. 2. Radioactive contamination contaminating six cities around Fukushima city (trends in natural logarithm form).

conducting a likelihood ratio (LR) test. Pooling the data imposes restriction that β is the same across each sub-period. A rejection of this restriction means it is not necessary to pool the data – β is not the same in each sub-period so it is admissible to run separate cross-sectional regressions. If, on the other hand, it is impossible to reject the null hypothesis that the β values are the same, then the data should be pooled and an appropriate panel methods should be used.

In this study, panel regressions are carried out and the null hypothesis of a common β is rejected on every occasion of sub-periods except the entire period so it is admissible to keep the data separate and estimate separate β coefficients. It is also worth to note here that one of the fundamental assumptions of the classical approach to convergence is that the growth rates are homogeneous, meaning all cities converge to different levels of radioactive contamination but at the same rate. The homogeneity assumption was criticized by Lee et al. [36] that poses a serious problem due to leading biased estimates of the speed of convergence. Dobson and Ramlogan [2] second this argument highlighted that it is possible to overcome the problem by developing a stochastic model of growth that formalizes the notion of heterogeneity – countries, cities or regions may converge to different levels of growth rates. In time series analysis, both trend stationary and difference stationary models strongly reject the restriction of a common growth rate across a large sample of countries. While the econometric implications of growth rate heterogeneity are a clearly important issue a detailed examination of the questions raised by Lee et al. [36] is beyond the scope of this study.

5.1. Panel unit root tests

Initially, the conventional Augmented Dickey-Fuller (ADF) test [37,38] was used to investigate the convergence hypothesis in level of radioactive contamination for different cities. Stationarity means that any time series data can be thought of as being generated by a stochastic or random process. An alternative test of stationarity that has recently become popular is known as the *unit root test*, which is broadly discussed by Dickey and Fuller [38]. In this study we applied panel unit root tests with lagged differences (10 lags) for testing the existence of any unit root problem in radioactive contamination series. The number of lagged difference terms to be included is often determined empirically, the idea being to include enough terms so that the error term in an equation is serially independent. Panel unit root tests with and without trend for all cities are proceeded for this study. As mentioned above, the test results are tabulated in Tables 1–4.

The results of regression analyses aimed at testing the convergence hypotheses for the all cities are presented in Tables 5 and 6. The results in Table 5 reveal that for all cities the β convergence is not realized for the entire period. However, significant and more meaningful β convergences have been obtained for all separate individual periods. The beta (β) coefficients are calculated with a formula described in Section 2 of this study. The calculated β coefficient indicates the percentage of the distance towards the common growth rate is being covered during one period. Keeping in mind that β coefficient indicates us what percentage of the distance towards the common growth rate of radioactive contamination among cities is being covered during one period.

The 0.00052 percent of β coefficient indicates that the distance towards the common growth rate of radioactive contamination has been covered per hour by all cities for the sub-period of 15–21 March 2011 (first week of nuclear meltdown). When we convert hourly speed of convergence into daily, weekly, monthly and annual bases, the speed of convergence becomes 0.01248, 0.08736, 0.3744 and 4.54272 respectively. For example, the speed of convergence of 8.7 percent per week is extremely high and very dangerous. These results reveal that the radioactive contamination in the first week spread over very quickly and endanger human life, therefore caused an emergency evacuation. The R^2 equaled 0.73 is quite significant when the *p*-value of the explanatory variable is within 1 percent significance interval (0.000). The results for the first half of the second week (22–24 March 2011) also confirms the beta convergence with a β coefficient of 0.00115 indicating that the distance towards the common growth rate of radioactive contamination has been covered much faster rate than the ones in the first week. The hourly speed of convergence for daily, weekly, monthly and annual periods are equalized as 0.0276, 0.1932, 0.828 and 10.074 correspondingly.

The results for the second half of the second week (25–27 March 2011) also validates the beta convergence. The estimated β coefficient for this period is 0.03688 per hour which is relatively faster than all the previous periods. The results indicate that the distance towards the common growth rate of radioactive contamination has been covered much faster rate than the previous period. The hourly speed of convergence for daily, weekly, monthly and annual periods are equalized as 0.88512, 6.19584, 26.5536 and 323.0688 respectively. The results proved the acceleration effect of radioactive contamination due to consecutive nuclear meltdowns of the additional reactors. It has been well understood that the technological constraints and the expertise competence were not adequate for complete decommissioning of Daiichi nuclear reactors.

For the sub-period of 15–21 March (first week of meltdown) the R^2 value is obtained as 0.73, and for the first and second half of the second week period the R^2 values are estimated as 0.05 and 0.039 correspondingly which are all significant at 1 percent significance level with 0.000 *p*-values.

In summary, all β coefficients are found to be significant for all sub-periods but not for the entire period. The results for the entire period did not have any expected negative sign although the constant value is found to be significant (0.003) with a very high *t*-statistics (7.330).

As far as σ convergence is concerned, both the entire period and all other sub-periods have been analyzed and in all cases σ convergence have been observed.

Table 6 demonstrates σ convergence results for all periods and as expected the trend line has all negative slopes for each period. These results of σ convergence estimations apply for both nearby (20 km) and distant (60 km) cities of Fukushima Prefectures.

The radioactive contamination growth paths in the cities of surrounding Fukushima during the entire period of 15–27 March 2011 do confirm the σ convergence hypothesis. It is worth stressing here that contamination level differentials of radioactive leakage among cities have been narrowed. The σ coefficient for all cities for the entire period of 15–27 March 2011 was found to be negative (−0.0015) and significant with high t-statistics value (−5.910). The trend line for the whole period slopes negatively with the R^2 coefficient equal to 0.201 and a significant explanatory variable with p-value (0.000). The findings over here are in line with the β convergence hypothesis. The cities that had been less contaminated in the beginning of meltdown on 15 March, recorded on average more rapid contamination growth than the cities with higher initial contamination levels. The development level of contamination in some cities was very low at the beginning of meltdown, but it grew very rapidly within 48 h. The fastest growth occurred mainly in the beginning of the second week, which caused huge level of contaminations with an accelerated rate of leakages due to consecutive meltdowns of other nuclear reactors.

As far as σ convergence is concerned for the sub-period of 15–21 March 2011 (first week of the explosion), the σ coefficient of −0.209 has also been found significant with high t-statistics value (−8.430) and significant R^2 value equaled 0.334. The estimated p-value (0.000) for this period also confirms the reliability of the estimations with 1 percent significance level for the estimation of explanatory variable.

The results for the first half of the second week (22–24 March 2011) also confirm the σ convergence with a σ coefficient of −0.0642, with a very significant t-statistics value (−8.430) and the R^2 value equaled 0.408.

The results for the second half of the second week (25–27 March 2011) also validate the σ convergence. The estimated σ coefficient for this period is −0.0487 which has been found significant with t-statistics value (−1.600) and significant R^2 value equaled 0.084. Both t-statistics and R^2 value are obtained relatively lower than the other sub-periods but all estimation results are found to be statistically meaningful with significant p-value (0.000) which confirms the reliability of the estimations with 1 percent significance level for the estimation of explanatory variable. As in all cases the σ convergences have been realized; this situation validates the convergence hypothesis.

6. Conclusion

As mentioned previously, about 53 percent of buildings were affected by seismic intensity 6 and above, with 15.2 percent of the buildings and 7.6 percent of the farms destroyed by the tsunami in Fukushima Prefecture. The engineers from Toshiba and Hitachi estimated that it will take between 10 and 30 years to complete decommissioning Fukushima Daiichi nuclear reactors with an estimated cost of more than 12 billion US dollars [14]. For compensation, an estimated 124 billion US dollars was paid by TEPCO to the victims of Fukushima residents. Domestic and foreign tourists visiting the region has dropped by 50–60 percent [39] following the disaster, and farming and fishing communities have suffered income losses due to the spread of radiation and loss of public trust in food safety. Livestock within the evacuation zone has also been abandoned and all animals that remain alive have lost their economic value.

The nuclear meltdown also exposes the fragility and contradictions in Japan's energy policy and misplaced optimism of post-war assumptions that economic expansion and advanced technology would provide solutions to the problems associated with Japan's accelerated economic development model. The country now lacks significant energy resources of its own and is, therefore, vulnerable to political volatility overseas.

Mistakes in tsunami evacuation are being examined and procedures are being enhanced to prevent Japan from inadequate safety equipment which were hiding behind contracts by the so called nuclear gypsies and other vulnerable groups. New defensive infrastructure is already being improved and new technologies are being developed and employed. Beyond this, community reconstruction will also make settlements safer by building compact communities on higher land and by developing safer buildings and neighborhoods in low-lying areas. The top-down delivery of hard reconstruction will be more effective and efficient. The compliance issues of nuclear security has to be prepared and better quality assurance measurements have to be enforced at national level. A disaster containment policy and organization should be formed with more central supervision and coordination.

There will be competition for financial, material, technical, labor and land resources within the affected region. As the reconstruction gets underway in Japan, all costs will go up and the speed and scope of the recovery will be constrained. More pragmatic compromises between divergent interests, established procedures and regulations, and deeply held principles need to be required in Japan. In the short and medium-term, Japan will be more dependent on fossil fuels which will increase the cost of electricity production, with an additional 15 percent reduction in personal energy consumption. Electricity production with fossil fuels will surely increase carbondioxide emissions and then threaten the sustainability of environment with global warming. There is no doubt that the government of Japan should facilitate more renewable energy resources for the near future. It is certain that less nuclear energy capacity elsewhere, and the difficulty of persuading municipalities to accept new stations or reactors will all restrict Japan's ability to replace fossils fuels. Moreover, a shift towards renewables will not come about suddenly and will cost money, which Japan needs for recovery and reconstruction. Heavy debt burden of Japan will cause more prolonged and painful recovery.

The time-series analysis and econometric tests reported in this study indicate significant evidence of both β and σ convergences among six cities of Fukushima Prefecture as also summarized in Fig. 3. The results of σ convergence estimations for all cities reveal that the σ coefficient was found to be significant both for the entire (15–27 March 2011) and all sub-periods (22–24 and 25–27 March). This evidence of real convergence or narrowing the existing gaps in radioactive contamination of all cities were realized as a result of loss of cooling systems due to the breach of the protective walls at the Fukushima Daiichii nuclear power plant during 17 m high of tsunami. The subsequent meltdowns of nuclear reactors and continuous hydrogen explosions that tore apart the buildings housing reactors 1, 3 and 4 have speeded the contamination growth which were measured by the β convergences.

For all regions, the β convergence tests were performed, and no β convergence has been found for the entire period, but very significant β convergences have been obtained for the sub-periods (first week, first and second half of the second week). This means, the empirical findings indicate that radioactive contamination growth paths among all the cities of Fukushima Prefecture have exhibited very strong converge growth patterns for all sub-periods. The σ coefficient was also found to be significant for the entire and all other sub-periods. This evidence of real convergence or narrowing the existing gaps in radioactive contamination levels was found among all cities of Fukushima.

Furthermore, the β coefficient corresponding to the period of March 15–21 (the first week of nuclear meltdown) and the β coefficients (0.001 and 0.03688) for the corresponding periods of March 22–24 and 25–27 have validated the unconditional

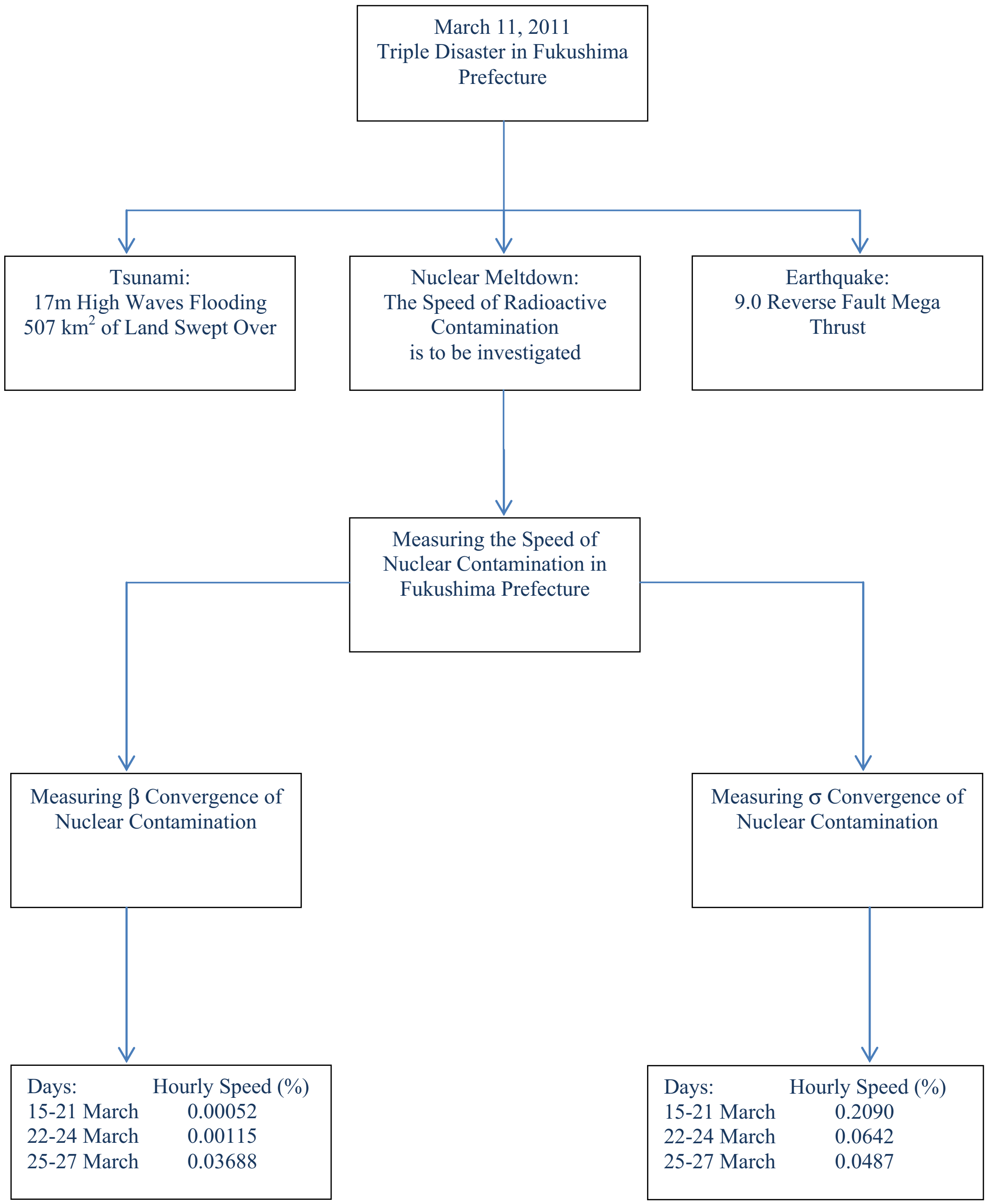

Fig. 3. Radioactive convergence of nuclear leakage in Fukushima.

radioactive convergence among the regions of Fukushima Prefecture. Research findings also reveal that the radioactive contamination in the first week spread over very quickly which endangered life very seriously. The β coefficient (0.03688 per hour) for the period of March 25–27 deserves more serious attention when hourly speed of convergence are equalized for daily, weekly, monthly and annual periods that corresponds 0.88512, 6.19584, 26.5536, and 323.0688 times fold respectively.

The results regarding σ convergence for the same corresponding periods also validated the convergence hypothesis with significant coefficients (-0.0642, -0.0487, and -0.2090). The hypothesis of radioactive contamination differences which are measured by the standard deviation of nuclear radioactive contamination level among the cities of Fukushima Prefecture has also been accepted.

The impact of earthquake and seismic intensity has been measured by the Richter scale. Scientists also managed to measure the impact of tsunami damages through calculating the height and distance of waves flooding over the low lying coast of areas of the seaboard of Honshu. This research however, contributes to the literature by computing the speed of radioactive contamination beyond the vicinity of the Fukushima's plant as a result of nuclear leakages from the reactors. With this research, the speed of radioactive contamination caused by nuclear meltdown has been measured. This may help scientists, economists and policy makers for post-disaster reconstruction and food security.

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